SOME OBSERVABLE INDICATORS OF s-PROCESS ENVIRONMENTS?

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1. ABSTRACT

By definition, the chemically peculiar stars have element abundances that are non-solar. Many of these stars show peculiarities in s-process elements. This paper discusses observable indicators of the neutron environment for the s-process in these stars.

2. ISOTOPIC INDICATORS?

The neutron sources usually considered for producing s-process elements are ^{13}C and ^{22}Ne (Cameron, 1955; Burbidge, Burbidge, Fowler, and Hoyle, 1957...). Cowan and Rose (1977) have suggested that under certain conditions ^{14}C might be produced in observable quantities if ^{13}C were the neutron source. However, they ignored neutron reactions on all elements heavier than ^{16}O (Despain, 1977), which cause a reduction in ^{14}C production of at least a factor of about 50 (Despain, unpublished).

Scalo and Miller (1981) proposed that ^{99}Tc could be used as an indicator of the nucleosynthesis and mixing processes in thermally-pulsing red giants, using ^{22}Ne as a neutron source. However, they did not take into account the enhanced beta decay of ^{99}Tc in the hot stellar interior, which places their interpretation of its detection in doubt (Cosner, Despain, and Truran, 1984).

3. ELEMENTAL INDICATORS

Elemental indicators have previously been discussed by Butcher (1976) and Cowley & Downs (1981); their indicators give a measure of the total neutron exposure, τ--defined by Clayton, Fowler, Hull, and Zimmerman (1961)--but not of the neutron density, n. The following presents an s-process indicator for measuring both τ and n. Assuming the peculiar abundance observed, $\{X_*\} \equiv (X_*/Fe_*)/(X_r/Fe_r)$ is the consequence of mixing an ordinary (i.e., "solar like") envelope of mass M_e with abundances

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X_e, with a shell of mass M_s, with s-process abundances, X_s, where X_r is the abundance in a reference star, $\{X_*\}$ is given, after some algebra, by

$$\{X_*\} - R = fR\,(X_s/X_e - 1) \quad , \tag{1}$$

where $f = M_s/(M_e + M_s)$ and $R = (X_e/Fe_*)/(X_r/Fe_r)$. Assuming $(X_e/Fe_e) = (X_r/Fe_r)$, $R = (Fe_e/Fe_*)$. A reasonable range for R is $1 \lesssim R \lesssim (1-f)^{-1}$, the limits being given by $Fe_s/Fe_e = 1$ and by $Fe_s/Fe_e = 0$. To eliminate the factor fR in Eq. (1) we examine ratios of elements. For the s-process, the proposed observables are

$$S_{12} \equiv \langle Sr+Y+Zr\rangle/\langle Ba+La+Ce\rangle \text{ and } S_{23} \equiv \langle Ba+La+Ce\rangle/\langle Nd+Sm+Eu+Gd\rangle, \tag{2}$$

where $\langle \Sigma X_i \rangle \equiv \Sigma(\{X_i\} - R)/N$. S_{12} is the ratio of the average enhancement of elements in the first s-process element peak, determined by the closed nuclear neutron shell at 50 to those in the second closed shell at 82. It is a measure of the neutron exposure, τ. S_{23} is the ratio of the average enhancement of elements in the second peak to a group of elements on the "plateau" after the peak. Since at a higher neutron density a nuclear shell will generally close at a lower atomic weight and (eventually) atomic number, this can serve as a measure of n.

4. COMPARISON WITH OBSERVATIONS

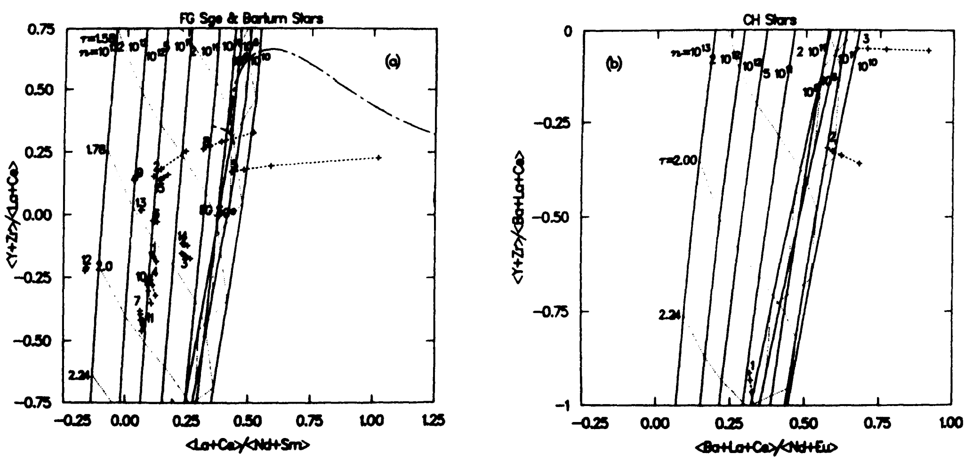

Figure 1. Theory vs Observation (see text for discussion)

Figure 1 compares observations and calculations for FG Sge (a), barium stars (a), and CH stars (b). The dashed curves are the observations with R = 1, 1.1, 1.25 and 1.5. The numbers correspond to the stars in Table I. The solid curves are calculations at constant neutron density, given across the top. The dotted curves connect the points on the curve at constant τ, as indicated on the left. These values of τ correspond to the number of neutrons per iron seed captured on all elements heavier than, and including, ^{22}Ne in the range from roughly 400 to 1000 (top to bottom). The chain dash curve is the loci of models of the thermally-pulsed ^{22}Ne source, as it operates in the AGB stars (Iben, 1976; Cosner, 1982; etc.). As can be seen, these stars appear to show a large range in neutron densities, but virtually all show neutron exposures too heavy for the AGB ^{22}Ne source. Note that a different set of elements is used in the definition of S_{12} and S_{23} than in section (4) because one (or more) abundance is missing for some of the stars.

Table I

#	Star	Reference (see reference section)	#	Star	Ref.	#	Star	Ref.	#	Star	Ref.
1	HD 46407	W	6	HD 178717	W	11	HD 204075	CD		FG Sge	LKA
2	HD 83548	W	7	HD 183915	W	12	HD 46407	BB	CH Stars		
3	HD 92626	W	8	HD 204075	W	13	HD 204075	T	1	HD 26	WG
4	HD 116713	W	9	HD 211594	W	14	HD 116713	D	2	HD 176201	SB
5	HD 175674	W	10	HR 774	C	15	HD 83548	D	3	HD 204613	SB

5. CONCLUSIONS

1. There are some potentially useful, observable s-process indicators.
2. Abundance measurements on as many of the elements in each of the sets (Sr,Y,Zr), (Ba,La,Ce), and (Nd,Sm,Eu,Gd) would be helpful in characterizing the s-process environment.
3. Barium stars, FG Sge, and CH stars have all apparently produced their s-process elements in quite rich neutron environments, with significant star to star variations.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Burbidge, EM and Burbidge, GR 1957, ApJ,126,357. (BB)
Burbidge, EM, Burbidge, GR, Fowler, WA, and Hoyle, F 1957, RMP,29,547.
Butcher, HR 1976, ApJ, 210, 489.
Cameron, AGW 1955, ApJ, 121, 144.
Clayton, D, Fowler, W, Hull, T, and Zimmerman, B 1961, Ann Phys, 12,331.
Cosner, KR 1982, PhD thesis, Univ. of Ill.
Cowan, JJ, and Rose, WK 1977, ApJ, 212, 149.
Cowley, CR, 1968 ApJ, 153, 169. (C)
Cowley, CR, and Downs, PL 1980, ApJ, 236, 648. (CD)
Danziger, I 1965, MNRAS, 131, 51. (D)
Despain, KH 1977, ApJ 212, 774.
Iben, I 1975, ApJ, 196, 549
Langer, G, Kraft, R, and Anderson, K 1974, ApJ, 189, 509. (LKA)
Scalo, J. and Miller, G 1981, ApJ, 246, 251.
Sneden, C, and Bond, H 1976, ApJ, 204, 810. (SB)
Tech, JL 1971, NBS Monograph 119. (T).
Wallerstein, G, and Greenstein, J 1964, ApJ, 169, 1163. (WG)
Warner, B 1965, MNRAS, 129, 263. (W)

DISCUSSION

Müller: The elements for which you wish to have very good abundance determinations are precisely some of those which are very difficult to determine: the non-LTE plays an important role in their spectral line formation, and for non-LTE calculations of spectral lines accurate atomic cross-sections are needed which, however, are not available and are very difficult to determine for these multilevel atoms.

Renzini: I think that Iben and Truran never suggested the ^{22}Ne source in connection with Barium stars. Indeed, much more neutrons per iron seed are produced in AGB stars of small core mass, where post-flash carbon/hydrogen semiconvection leads to the activation of the ^{13}C source.

Despain: The indicated neutron per iron seed for the Barium stars is 400-800, while the neutrons per iron seed indicated by Iben for the above mechanism was ~26, more than an order of magnitude too low for the indicated S_{12} parameter.

Acker: Using spectra of FG Sge taken in 1979-1982, I show that this star does not evolve toward a Barium star (as suggested), and I give new indications about s-process element abundances.

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